A Cooperative Scheduling Algorithm for the Coexistence of Fixed Satellite Services and 5G Cellular Network

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***Abstract*—The increasing demand for higher data rates has accelerated research on the next generation of mobile cellular networks (5G). One of the key factors of 5G is the use of a larger bandwidth allocated in the millimeter wave (mmWave) frequency spectrum. In particular, one of the candidate bands is the portion of spectrum between 17 and 30 GHz that is currently used by other technologies such as fixed satellite services (FSS) and the cellular network backhaul. In this paper, we analyze the coexistence between mobile services and FSS considering the main characteristics of the mmWave spectrum recently investigated in the literature. Moreover, we present a novel cooperative scheduling algorithm based on a game theoretic framework that exploits the use of analog beamforming at the base stations (BS). Finally, we show that adopting this algorithm ensure that the system meets the regulatory recommendation concerning the interference level at the FSS and at the same time provides a good user spectral efficiency.**

Keywords*—*Millimeter wave communication; cellular networks; radio spectrum management; satellite communication; beamforming.

I. Introduction

The increasing popularity of smart phones and mobile data devices has made mobile communication an indispensable part of life for billions of people, generating an unprecedented growth of fast connectivity demand [1]. The current generation cellular network, including LTE and LTE-Advanced, already adopts advanced technologies such as orthogonal frequency-division multiplexing (OFDM) and multi-input multi-output (MIMO) systems leaving limited room to further improvements [2]. Moreover, the current spectrum between 700 MHz and 2.6 GHz is saturated and an enlargement of the current systems bandwidth seems impossible within this frequency range. The most interesting candidate to face these challenges is the development of a new generation cellular network deployed in the mmWave spectrum [3]. Recent studies have demonstrated that exploiting the small wavelength of mmWave frequencies, it is possible to use large antenna arrays and overcome the large pathloss perceived within this portion of the spectrum [4][5] making the use of these frequencies feasible.

The spectrum between 17 and 30 GHz is one of the candidates for the deployment of the next generation cellular network. Currently, part of this band is allocated on a coprimary basis to fixed services (FSs) and fixed satellite services (FSS) [6]. The FSS uplink (from FSS to satellite) is allocated in the band from 27.5 to 30 GHz and the downlink (from satellite to FSS) is allocated from 17.3 to 21 GHz [7]. It is then important to study the coexistence between FSS and the cellular network to understand whether the mobile service operating within these frequencies may affect the functionalities of the satellite services. Similar investigations have been proposed by the international telecommunication union (ITU) for the spectrum sharing between FSS and IMT-advanced systems in the frequency band from 3.4 to 6.4 GHz [8][9].

In this work we present a novel cooperative scheduling algorithm for cellular BSs that, exploiting a game theoretic framework, regulates the FSS-cellular BSs coexistence maintaining the interference over noise level (I/N) at the FSS below the threshold indicated by the regulatory recommendations. In particular, we model the scenario as a potential game [10]. This technique has been applied recently in the literature to design several wireless network problems. For instance, a game theoretic solution based on potential games for joint channel selection and power allocation in cognitive radio networks is presented in [11]. Exploiting the potential game framework, a resource allocation scheme in a multicell OFDMA uplink scenario for energy-efficient power control is proposed in [12]. Moreover, a distributed potential game-based algorithm that addresses the minimum transmission broadcast problem in wireless networks is presented in [13].

Different from [14], where we study the effect of several system parameters on the performance of coexisting FSS and cellular systems, the aim of our work is to design a cooperative scheduling algorithm where each BS schedules one user considering the achievable spectral efficiency and the impact on the FSS I/N level. We develop our framework in the FSS downlink band considering the results provided in the literature on the mmWave spectrum [15][16] and the ITU recommendations. Moreover, our potential game formulation ensures equilibrium of user scheduling. We present three different versions of the algorithm: the first is based on throughout maximization, the second is based on FSS interference minimization, and the third considers both aspects. Finally, we show how, applying the algorithm proposed, it is possible to meet the regulatory recommendations and at the same time to reach a high level of spectral efficiency.

The paper is organized as follows. Section II describes the model considered, focusing on the standard system parameters used in the analysis, and Section III presents the cooperative scheduling algorithm proposed. Section IV gives the performance evaluation for the different scenarios considered. Finally, conclusions are drawn and future works are discussed in Section IV.

Remark: Throughout the paper, we use boldface letters for vectors and matrices, and we denote with $(\cdot)^T$ the conjugate transpose.

II. System Model

We consider the scenario depicted in Fig. 1 that corresponds to the downlink band of the FSS system at 18 GHz [14]. The cellular BSs are deployed in tiers around the FSS according to the BSs intersite distance d_i and the protection distance d_p that represents the distance between the FSS and the first tier of BSs. The users are distributed randomly within the BSs coverage area and each BS selects one user at a time. We assume that each BS and each UE are equipped with N_{UE} and N_{BS} antennas, respectively. We define as *primary link* the transmission from the satellite to the FSS while as *secondary link* the connection from a cellular BS to a mobile user equipment (UE). The FSS is subject to additional interference through the *interfering links* from the BSs to the FSS, given by the sum of all the interference generated by the BSs.

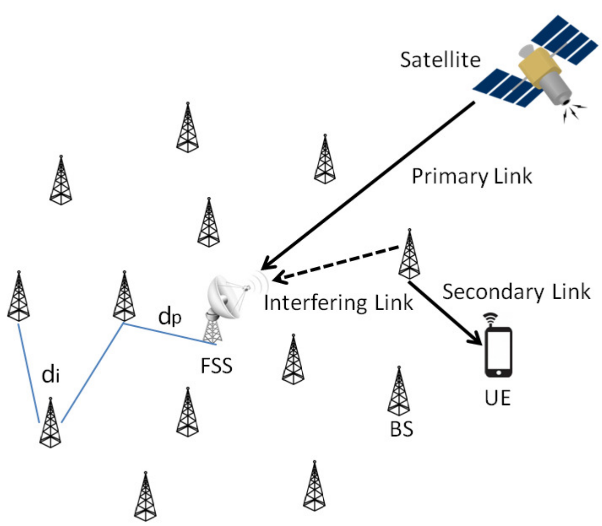

Fig. 1. FSS-BS coexistence scenario

The interference (on a log scale) generated by BS b to the FSS can be computed as

$$I_b = P_{BS} + G_{BS} + G_{FSS}(\phi) - L(d) \tag{1}$$

where P_{BS} is the BS transmission power, G_{BS} is the BS antenna gain, $G_{FSS}(\phi)$ is the FSS antenna gain in the direction ϕ, where ϕ is the angle between the main FSS antenna lobe and BS b, and $L(d)$ is the pathloss component at distance d which in turn is the FSS-BS distance.

According to [17] we adopt a double-directional geometry based stochastic model with L scatterers, where L is limited to a small number for a mmWave scenario. The $N_{UE} \times N_{BS}$ channel matrix $\mathbf{H}$ can be computed as

$$\mathbf{H} = \sqrt{\frac{N_{BS}N_{UE}}{L}} \sum_{\ell=1}^{L} \alpha_\ell \mathbf{a}_{UE}(\gamma_\ell^{UE}) \mathbf{a}_{BS}^*(\gamma_\ell^{BS}) \tag{2}$$

where α_ℓ is the complex gain of the ℓ^{th} path and $\gamma_\ell^{UE}, \gamma_\ell^{BS} \in [0, 2\pi]$ are uniformly distributed random variables that represent the angles of arrival and departure, respectively. Finally, $\mathbf{a}_{UE}$ and $\mathbf{a}_{BS}$ are the antenna array responses at the UEs and BSs, respectively. Assuming uniform linear arrays, $\mathbf{a}_{BS}$ can be written as

$$\mathbf{a}_{BS} = \frac{1}{\sqrt{N_{BS}}} \left[1, e^{j\frac{2\pi}{\lambda} D \sin(\gamma_l^{BS})}, ..., e^{j(N_{BS}-1)\frac{2\pi}{\lambda} D \sin(\gamma_l^{BS})}\right] \tag{3}$$

where D is the distance between antennas. Similarly, $\mathbf{a}_{UE}$can be computed by substituting N_{BS} and γ_ℓ^{BS} in (3) with N_{UE} and γ_ℓ^{UE}, respectively.

The BS antenna gain in dB is

$$G_{BS} = G_{omni} + G_{BF} \tag{4}$$

where G_{omni} is the conventional antenna gain when no beamforming techniques are applied. Conversely, G_{BF} is the beamforming gain and depends on the beam configuration selected by the BS controlling phase and magnitude of the input signal to each antenna and on the channel coefficients. We assume that the BSs can select the beam configuration within a predefined beam codebook with cardinality N_t that uniformly covers the azimuth directions. The codebooks at the transmitter and the receiver are formed by N_t and N_r weight vectors $\{\mathbf{v}_1, ..., \mathbf{v}_{N_t}\}$ $\{\mathbf{w}_1, ..., \mathbf{w}_{N_r}\}$ of size N_{BS} and N_{UE}, respectively. Each vector is computed as $\mathbf{v}_i = \mathbf{a}(\rho_i)$ and $\mathbf{w}_k = \mathbf{a}(\theta_k)$ where ρ_i and θ_k are the azimuth angles for the i-th transmit RF beam and k-th receive RF beam. We assume a multiple-input-single-output (MISO) scenario, in which the beamforming gain in the direction of the FSS antenna is

$$G_{BF} = 10\log(\left|\mathbf{v}_i^T \mathbf{h}_{FSS}\right|^2) \tag{5}$$

where $\mathbf{v}_i$ is the beamforming precoding vector selected by the BS and $\mathbf{h}_{FSS}$ is the channel matrix between the BS and the FSS.

The FSS antenna gain is computed as a function of the off-boresight angles, which can be calculated using the model in [18]. Considering ϑ as the azimuth of the BS w.r.t. the FSS Rx main lobe, the off-boresight angles ϕ of the BS towards the FSS can be calculated as

$$\phi = \arccos(\cos(\alpha)\cos(\epsilon)\cos(\vartheta) + \sin(\alpha)\sin(\epsilon)) \tag{6}$$

where α is the FSS elevation angle and ϵ is computed as

$$\epsilon = \frac{h_t - h_s}{d} - \frac{d}{2r} \tag{7}$$

where h_s and h_t are the heights of the BS and the FSS in meters, respectively, while r is the effective Earth radius ($\approx 8.5 \cdot 10^3$ km). The FSS off-boresight antenna gain pattern in dB can be computed as [19]

$$G_{FSS}(\phi) = \begin{cases} G_{max} & if\ 0^\circ < \phi < 1^\circ \\ 32 - 25 \log \phi & if\ 1^\circ \leq \phi < 48^\circ \\ -10 & if\ 48^\circ \leq \phi \leq 180^\circ \end{cases}$$

where G_{max} is the main beam axis FSS antenna gain.

The level of interference allowable at the FSS is regulated by ITU. For the "short term" interference, recommendation [20] indicates that interference from fixed service systems should not cause the BER to exceed 10^{-4} for more than 0.03% of any month nor cause the BER to exceed 10^{-3} for 0.005% of any month. These interference allowances, in terms of percentage of system noise, can be converted into corresponding values of I/N, leading to -2.4 and 0 dB, respectively. To evaluate the performance of our algorithm, we consider the regulatory recommendation for the "long term" interference that refers to a percentage of time greater than 20%. In this case, recommendation [20] allows an interference that would give rise to a BER of 10^{-6}. The value for 20% of the time is computed in [21] and is equal to -10 dB.

III. COOPERATIVE SCHEDULING ALGORITHMS

In this section we describe the cooperative scheduling algorithm proposed. The aim of this algorithm is to improve the BSs-FSS coexistence reducing the minimum d_p required to satisfy the standard interference limit threshold at the FSS. The main idea is to coordinate the user transmissions in order to control the interference at the FSS and at the same time preserve the user average spectral efficiency. The interactions among the BSs can be modelled using a game theoretic framework. In particular, by modelling the scenario as an exact potential game, it is possible to ensure that a pure Nash equilibrium can be reached [10][11]. A characteristic of a potential game is that any unilateral change of utility, $U(s_i, s_{-i})$, corresponds to a difference of a potential function, $F(s)$, for every player and for every choice of the other players. The potential function models the information associated with the improvement paths of a game instead of the exact utility of the game. Our scenario can be modelled in a normal form game $\Gamma = \{B, \{S_i\}_{i \in B}, \{U_i\}_{i \in B}\}$, where each player corresponds to a BS, B is the set of players and therefore the number of BSs, and $S_i = \{1, 2, ..., K\}$ is the set of strategies of player i. Considering that K users are deployed within the coverage area of a player i, the strategy played by i consists of the selection of a specific user within the K deployed in its area. For every player i in Γ, the utility function U_i is a function of strategy s_i selected by player i, and the strategies of the other players, globally denoted as s_{-i}.

In our algorithm we assume that the actions of the players are taken sequentially by randomly selecting one player in each algorithm iteration. The procedure terminates when the algorithm converges to a stable scheduling configuration. We also assume that each BS has a global knowledge of the system parameters that is exploited to optimize the utility function, and that the channel conditions are constant during each algorithm realization. When a BS is selected, the user that maximizes the BS's utility function is scheduled. We emphasize that, if the game considered corresponds to an exact potential game, the equilibrium convergence is guaranteed and the configuration of the users scheduled is stable. We define three different approaches based on three different utility functions: a maximum rate approach (MaxRate), a minimum interference approach (MinInt) and finally an algorithm based on the linear combination of the previous ones (LinComb).

The aim of the first algorithm is to maximize the mean spectral efficiency of the users considering within the utility function the signals received by the selected user and the intercell interference. In this case, we define the utility of player i given a certain strategy s_i as

$$\begin{aligned} U_i^{MR}(s_i, s_{-i}) = p_{ji} \left| \mathbf{v}_i^T \mathbf{h}_{ji} \right|^2 - \sum_{b=1, b \neq i}^{B} p_{jb} \left| \mathbf{v}_b^T \mathbf{h}_{jb} \right|^2 \\ - \sum_{m=1, m \neq j}^{M} p_{mi} \left| \mathbf{v}_i^T \mathbf{h}_{mi} \right|^2 \end{aligned} \quad (8)$$

where j is the user scheduled by BS i when strategy s_i is adopted and p_{ji} is the power at user j transmitted from i. The utility function consists of three terms. The first term represents the power received by the user scheduled by i, the second term indicates the inter-cell interference received by user j and, the third term represents the interference generated by i on the users scheduled by the other BSs.

Conversely, the aim of the MinInt algorithm is to minimize the FSS interference. In this case the utility function is:

$$U_i^{MI}(s_i, s_{-i}) = -\xi(I/N) \quad (9)$$

where $\xi(I/N)$ is a function of the interference generated by the BSs to the FSS. In particular I/N is defined as:

$$I/N = \sum_{b=1, b \neq i}^{B} I_b - N \quad (10)$$

where I_b is defined in (1) and N is the noise level. The function $\xi(I/N)$ is designed in order to penalize the strategies that generate large interference at the FSS and to provide more flexibility to the users selection if the FSS interference is lower than the recommended threshold. $\xi(I/N)$ is set as

$$\xi(I/N) = \begin{cases} 0 & if\ I/N < I/N_0 \\ \frac{I}{1 - e^{-(I/N - I/N_0)}} & if\ I/N \geq I/N_0 \end{cases}$$

where I/N_0 is fixed to a value lower than the recommended I/N threshold, -12 dB, in order to control the interference at the FSS.

Finally, we define the LinComb algorithm where the effects on the users and on the FSS are considered together. In this

TABLE I. MAIN SYSTEM PARAMETERS

Parameter	Value
Carrier frequency	18 GHz
Total downlink bandwidth	500 MHz
BS transmit power	30 dBm
BS antenna height	20 m
BS omnidirectional antenna gain	6 dBi
BSs intersite distance	500 m
BS inter-antenna distance	$\lambda/2$
BS beam codebook cardinality	16
BS number of antennas	16
FSS antenna main lobe gain	42.1 dBi
FSS antenna diameter	2.4 m
FSS antenna height	2 m
Elevation angle	10°
Pathloss model	$61.39 + 10 \times 2.47 \log(d)$ [16]
Number of scatterers	3
Noise temperature	300 K
Number of users per BS	10
Recommended I/N level	-10 dB

case, the utility function is

$$U_i(s_i, s_{-i}) = p_{ji} \left|\mathbf{v}_i^T \mathbf{h}_{ji}\right|^2 - \sum_{b=1,b\neq i}^{B} p_{jb} \left|\mathbf{v}_b^T \mathbf{h}_{jb}\right|^2 - \sum_{m=1,m\neq j}^{M} p_{mi} \left|\mathbf{v}_i^T \mathbf{h}_{mi}\right|^2 - \beta\xi(I/N) \qquad (11)$$

where β is an adjusting parameter.

For all the algorithms it is possible to define an exact potential function that leads to a specific potential game. The proof is reported in the Appendix.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance reachable with the cooperative scheduling algorithm. In particular, we study the results achievable by the LinComb algorithm in terms of I/N level at the FSS and of mean spectral efficiency of the users. We assume that the total downlink bandwith is 500 MHz and the BSs allocate the power uniformly over this bandwith. The pathloss model is given exploiting the results presented in [16] on the mmWave band. Assuming a system effective noise temperature $\mathtt{T}$ equal to 300 K, the one-sided noise power spectral density value results equal to $\mathtt{kT} = -143.82$ dBW/MHz, where $\mathtt{k}$ is the Boltzmann constant.

We assume that three tiers of BSs are deployed around the FSS and 10 user are randomly deployed within each BS coverage area. The number of antennas for each BS is fixed to 16. Considering the expected cell coverage in next generation cellular networks [22] we assume $d_i = 500$ m. We emphasize that the markers reported in the graphs are used just to improve the curve visualization. The detailed system parameters are reported in Table I.

Fig. 2 shows the evolution of the I/N level at the FSS for the different potential game algorithms proposed using the same configuration of users and starting from the same random set of scheduled users. As expected, the I/N level for the MinInt algorithm converges around I_0 since there is no reward for the BSs to schedule users that generate interference at the FSS. Conversely, the utility of the MaxRate algorithm is related just to the spectral efficiency of the users and the I/N level converges to a higher value. Finally, the LinComb algorithm achieves an intermediate I/N value. We emphasize that the converging values of the MinInt and LinComb algorithms can be modified selecting a different I_0 value.

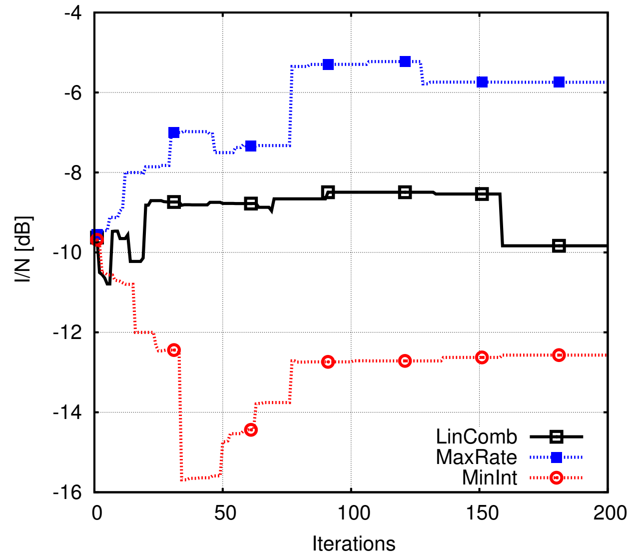

Fig. 2. I/N evolution for the different algorithms considered

Fig. 3 describes the CDF of the I/N level at the FSS. The results have been obtained via Monte Carlo simulations using a different users configuration for each realization. As expected, the performance achieved by the MaxRate algorithm are above the limit imposed by regulations since there is no constraint on the interference at the FSS. Conversely, for the MinInt algorithm the I/N level is maintained under the -10 dB threshold recommended by the standard. Using the LinComb algorithm the standard threshold is achieved for almost 60% of the user configurations getting a significant improvement in comparison with the MaxRate case.

Fig. 4 shows the CDF of the user spectral efficiency ν for the different algorithms considered. As expected, the MinInt and MaxRate algorithms obtain the worst and the best results, respectively. Conversely, the PG algorithm achieves a result very close to the MaxRate algorithm even though, as depicted in Fig. 3, the interference at the FSS is maintained at low values. Thus, the LinComb algorithm provides a good tradeoff between guaranteeing a high user spectral efficiency and achieving an acceptable interference level at the FSS. Besides, by properly selecting the parameters I_0 and β, it is possible to regulate the BSs-FSS coexistence and to reduce the protection distance to increase the mmWave network coverage area.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we investigated the coexistence feasibility of FSS and cellular BS in a mmWave scenario using a novel

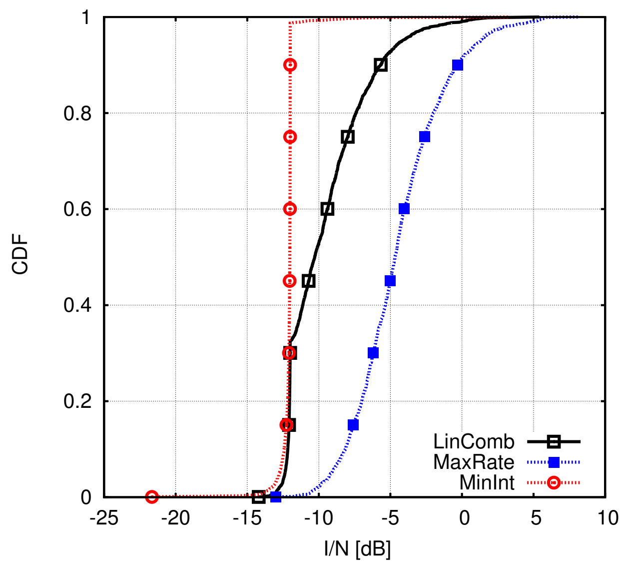

Fig. 3. I/N CDF for the different algorithms considered

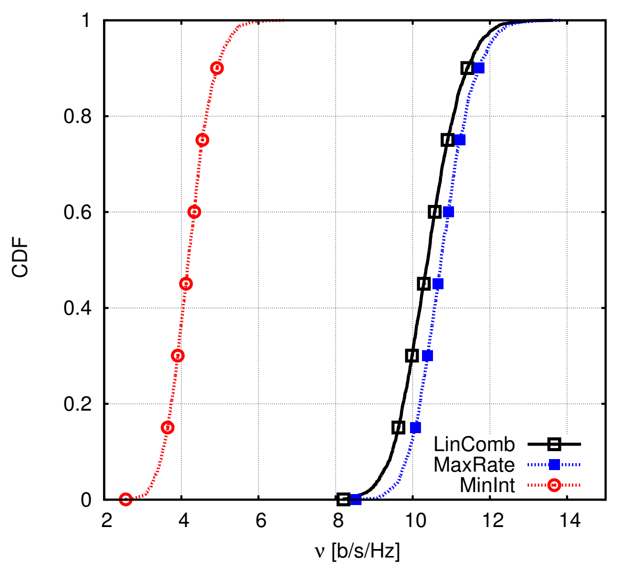

Fig. 4. ν CDF for the different algorithms considered

cooperative scheduling algorithm based on a game theoretic framework. We showed that coordinating the BS scheduling and exploiting the characteristics of the mmWave spectrum, it is possible to meet the interference regulatory recommendations at the FSS and to achieve a good spectral efficiency at the users.

As future work, we intend to develop possible distributed cooperative algorithms of beamforming and scheduling among the BSs to mitigate the interference at the FSS and to reduce the required signalling among the BSs. Moreover, more complex scenarios such as heterogeneous networks and more realistic BS deployment could be considered.

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Appendix

In order to show that the problems presented in Section III can be treated as potential games, we have to define a potential function for each scenario able to satisfy the propriety

$$U_i(s_i, s_{-i}) - U_i(s_i', s_{-i}) = F(s_i, s_{-i}) - F(s_i', s_{-i}) \quad (12)$$

Considering the set of BSs $\{1, ..., B\}$ and denoting as q the user scheduled by BS k with $k \in \{1, ..., B\}$, we can define $F(S)$ for the MaxRate algorithm as

$$\begin{aligned} F(S) &= F(s_k, s_{-k}) \\ &= \sum_{i=1}^{B} (p_{ji} \left|\mathbf{v}_i^T \mathbf{h}_{ji}\right|^2 - \alpha \sum_{b=1, b\neq i}^{B} p_{jb} \left|\mathbf{v}_b^T \mathbf{h}_{jb}\right|^2 \\ &\quad - (1-\alpha) \sum_{m=1, m\neq j}^{M} p_{mi} \left|\mathbf{v}_i^T \mathbf{h}_{mi}\right|^2) \end{aligned}$$

with $0 < \alpha < 1$.

It is possible to isolate the terms depending on s_k as

$$\begin{aligned} F(S) &= \\ &= p_{qk} \left|\mathbf{v}_k^T \mathbf{h}_{qk}\right|^2 - \alpha \sum_{b=1, b\neq k}^{B} p_{qb} \left|\mathbf{v}_b^T \mathbf{h}_{qb}\right|^2 \\ &\quad - (1-\alpha) \sum_{m=1, m\neq q}^{M} p_{mk} \left|\mathbf{v}_k^T \mathbf{h}_{mk}\right|^2 \\ &\quad + \sum_{i=1, i\neq k}^{B} (p_{ji} \left|\mathbf{v}_i^T \mathbf{h}_{ji}\right|^2 - \alpha \sum_{b=1, b\neq i}^{B} p_{jb} \left|\mathbf{v}_b^T \mathbf{h}_{jb}\right|^2 \\ &\quad - (1-\alpha) \sum_{m=1, m\neq j}^{M} p_{mi} \left|\mathbf{v}_i^T \mathbf{h}_{mi}\right|^2) \\ &= p_{qk} \left|\mathbf{v}_k^T \mathbf{h}_{qk}\right|^2 - \alpha \sum_{b=1, b\neq k}^{B} p_{qb} \left|\mathbf{v}_b^T \mathbf{h}_{qb}\right|^2 \\ &\quad - (1-\alpha) \sum_{m=1, m\neq q}^{M} p_{mk} \left|\mathbf{v}_k^T \mathbf{h}_{mk}\right|^2 \\ &\quad + \sum_{i=1, i\neq k}^{B} (p_{ji} \left|\mathbf{v}_i^T \mathbf{h}_{ji}\right|^2 - \alpha p_{jk} \left|\mathbf{v}_k^T \mathbf{h}_{jk}\right|^2 \\ &\quad - \alpha \sum_{b=1, b\neq i,k}^{B} p_{jb} \left|\mathbf{v}_b^T \mathbf{h}_{jb}\right|^2 - (1-\alpha) p_{qi} \left|\mathbf{v}_i^T \mathbf{h}_{qi}\right|^2 \\ &\quad - (1-\alpha) \sum_{m=1, m\neq j,q}^{M} p_{mi} \left|\mathbf{v}_i^T \mathbf{h}_{mi}\right|^2) \end{aligned}$$

Let

$$Q(s_{-k}) = \sum_{i=1, i\neq k}^{B} (p_{ji} \left|\mathbf{v}_i^T \mathbf{h}_{ji}\right|^2 - \alpha \sum_{b=1, b\neq i,k}^{B} p_{jb} \left|\mathbf{v}_b^T \mathbf{h}_{jb}\right|^2 - (1-\alpha) \sum_{m=1, m\neq j,q}^{M} p_{mi} \left|\mathbf{v}_i^T \mathbf{h}_{mi}\right|^2)$$

Then

$$\begin{aligned}
F(S) &= p_{qk} \left|\mathbf{v}_k^T \mathbf{h}_{qk}\right|^2 - \alpha \sum_{b=1, b\neq k}^{B} p_{qb} \left|\mathbf{v}_b^T \mathbf{h}_{qb}\right|^2 \\
&- (1-\alpha) \sum_{m=1, m\neq q}^{M} p_{mk} \left|\mathbf{v}_k^T \mathbf{h}_{mk}\right|^2 \\
&- \sum_{i=1, i\neq k}^{B} (\alpha p_{jk} \left|\mathbf{v}_k^T \mathbf{h}_{jk}\right|^2 + (1-\alpha) p_{qi} \left|\mathbf{v}_i^T \mathbf{h}_{qi}\right|^2) \\
&+ Q(s_{-k}) - \beta\xi(I - I_o) \\
&= p_{qk} \left|\mathbf{v}_k^T \mathbf{h}_{qk}\right|^2 - \sum_{b=1, b\neq k}^{B} p_{qb} \left|\mathbf{v}_b^T \mathbf{h}_{qb}\right|^2 \\
&- \sum_{m=1, m\neq q}^{M} p_{mk} \left|\mathbf{v}_k^T \mathbf{h}_{mk}\right|^2 + Q(s_{-k}) - \beta\xi(I - I_o)
\end{aligned}$$

Since the term $Q(s_{-k})$ is independent of the strategy of BS k, if BS k changes the scheduled user from q to q' we obtain:

$$\begin{aligned}
&F(s_k, s_{-k}) - F(s'_k, s_{-k}) \\
&= p_{qk} \left|\mathbf{v}_k^T \mathbf{h}_{qk}\right|^2 - \sum_{b=1, b\neq k}^{B} p_{qb} \left|\mathbf{v}_b^T \mathbf{h}_{qb}\right|^2 \\
&- \sum_{m=1, m\neq q}^{M} p_{mk} \left|\mathbf{v}_k^T \mathbf{h}_{mk}\right|^2 - \beta\xi(I - I_o) \\
&- \Bigg(p_{q'k} \left|\mathbf{v}_k^T \mathbf{h}_{q'k}\right|^2 - \sum_{b=1, b\neq k}^{B} p_{q'b} \left|\mathbf{v}_b^T \mathbf{h}_{q'b}\right|^2 \\
&- \sum_{m=1, m\neq q'}^{M} p_{mk} \left|\mathbf{v}_k^T \mathbf{h}_{mk}\right|^2 - \beta\xi(I' - I_o) \Bigg)
\end{aligned}$$

that is equal to $U_k(s_k, s_{-k}) - U_k(s'_k, s_{-k})$.

For the MinInt algorithm the potential function can be easily set equal to its utility function leading directly to a potential game. Finally, the potential function for the LinComb algorithm is the sum of the two potential functions considered before and the proof is straightforward.

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